



## Commentary on an Article by *Kwon TK, et al.*: “First-Order Mathematical Correlation between Damping and Resonance Frequency Evaluating the Bone-Implant Interface”

In-Sung Luke Yeo\*

Department of Prosthodontics and Dental Research Institute, Seoul National University School of Dentistry, Korea

### Abstract

A recent study on implantology reported a statistical linear correlation between two measures at the bone-implant interface: Periotest evaluation of the damping effect at the interface and resonance frequency analysis. The publication formulated a linear function of the dependent variable, the Periotest value (PTV), to the independent variable, the implant stability quotient value, by homogenizing the density of bone blocks and thoroughly controlling the engaged depth of implants inserted into these blocks. A correlation such as this can be mathematically explained using a second-order differential equation to describe a mechanical vibration model in physics; free vibration with damping. Although several clinical studies have found no significant correlation between the two values, it is important to investigate the reasons for the discrepancy between theory and experimental results in order to understand the nature of the bone around an implant.

**Keywords:** Bone-implant interface; Periotest; Resonance frequency analysis; Correlation

### Commentary

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##### \*Correspondence:

In-Sung Luke Yeo, Department of Prosthodontics and Dental Research Institute, Seoul National University School of Dentistry, 101, Daehak-ro, Jongro-gu, Seoul 03080, Korea, Tel: 82-2-2072-2661; Fax: +82-2-2072-3860; E-mail: pros53@snu.ac.kr

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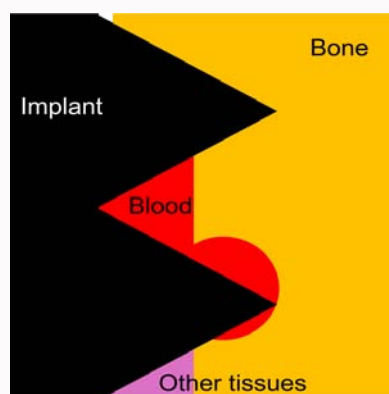
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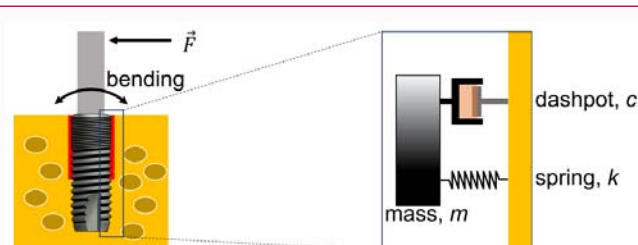
In a recent publication, “First-order mathematical correlation between damping and resonance frequency evaluating the bone-implant interface,” Kwon et al. [1] found a statistical linear correlation between the Periotest and implant stability quotient values. The Periotest device (Gulden Messtechnik, Bensheim, Germany) evaluates the quality of the bone-implant interface using the damping effect at the interface. When the implant firmly contacts the bone, the damping effect becomes smaller, which reduces the Periotest value (PTV) (the overall PTV range is from -8 to 50) [2,3]. Resonance frequency analysis can detect the frequency of the peak output amplitude responsive to input signals, which varies depending on the quality of the interface between the implant and the bone [3,4]. This frequency is used to derive the implant stability quotient (ISQ) value, which is higher (within an overall range from 0 to 100) for more stable bone-implant interfaces. Although the authors formulated a linear equation showing a statistical correlation between the PTV and the ISQ value [1], this finding is in conflict with many studies that have found little or no significant correlation even though the two values would intuitively seem to be associated [5].

It appears that a mathematical relation can be derived between the resonance frequency and damping effect at the bone-implant interface. The primary devices used for resonance frequency analysis (Osstell, Integration Diagnostics AB, Sävedalen, Sweden) and damping effect estimation both use reflective outputs based on vibrational inputs applied to the bone-implant interface. When an implant is placed in the bone, three interface layers must be considered: the implant, bone, and an in-between layer filled with blood, blood clot, fibrous tissue, or other tissues (Figure 1). When the relative size of the in-between layer grows, the implant becomes unstable, resulting in a change in resonance frequency and a larger damping effect. Thus, the reflective response to the vibrational inputs at the interface can be interpreted using a mass-spring-damper model of mechanical vibration, which is a well-known model in physics (Figure 2).

The second-order differential equation for this model is  $m\ddot{x} + c\dot{x} + kx = 0$ , where  $m$  is the mass of the system,  $c$  is the damping constant,  $k$  is the spring constant,  $x$  is displacement, and  $\ddot{x}$  and  $\dot{x}$  are the second- and first-order time derivatives of  $x$ , respectively. The mass, damping, and spring constants are all positive. When the bone-implant interface is under damped, a situation that is



**Figure 1:** Schematic of the bone-implant interface. Direct contact of implant surface with the bone clinically equates to a stable implant. Empty space scan occur between the bone and the implant; these are often filled with blood (red area) or other tissues (pink area).



**Figure 2:** Schematic of an implant inserted into bone. The red area on the left represents a gap between the implant and bone, which results in a larger damping effect when force is applied to the implant. The clinical state of the implant inserted into the bone is considered to be physically equivalent to free vibration with damping, as shown on the right.  $m$ : mass of the system;  $k$ : spring constant;  $c$ : damping constant.

clinically common (the critically damped and over damped cases both indicate failed implants that can be considered to be mobile), the general solution for this equation is

$$x(t) = Ae^{-\frac{c}{2m}t} \left( B \cos \cos \frac{\sqrt{4mk - c^2}}{2m} t + C \sin \sin \frac{\sqrt{4mk - c^2}}{2m} t \right)$$

where  $A$ ,  $B$ , and  $C$  are constants.

From this solution, a mathematical relation is found between the resonance frequency,  $R_f$  and the damping constant,  $c$ :

$$R_f = \frac{\sqrt{4mk - c^2}}{4\pi m} = D\sqrt{1 - r^2}, \left( r = \frac{c}{2\sqrt{km}}, D: \text{constant} \right)$$

Using  $R_f = D\sqrt{1 - r^2}$ , a linear mathematical relation can be theoretically found using logarithms such as  $\ln R_f = \frac{1}{2}(1 - r^2) + E(\text{constant})$ . Assuming that  $\ln R_f$  is  $y$ , which is associated with the ISQ value, and that  $\ln(1 - r^2)$  is  $x$ , which is associated with the PTV, the equation can be expressed as  $y = ax + b$ , where  $a$  and  $b$  are constants. That is, a first-order function is obtained. The authors demonstrated a statistical proof of this using bone models with precisely controlled thickness and density [1]. Another study supported such a statistical correlation between PTVs and ISQ values and produced a similar linear function [3].

As the bone has a heterogeneous density distribution, and bone

quality differs for each individual, it is difficult to find the linear PTV-ISQ correlation from real-world selected sample groups. Nevertheless, is it logical to conclude that the damping effect and resonance frequency are insignificantly correlated in reality, as other studies have stated, despite the fact that the two phenomena are theoretically related through a differential equation based on a mechanical vibration model? [6-9]. It would be more rational to attempt to determine the following: how the real bone resorption pattern and bony contour differ from their respective theoretical counterparts; why the PTV-ISQ correlation deviates from the theoretically expected value according to bone quality; and what is the nature of osseointegration at the bone-implant interface. Addressing these questions will lead to the development of a more elaborately designed resonance frequency analyzer and damping effect estimator that can predict the crestal bone geometry around an implant and differentiate the simple initial contact of implant surface to bone from the bone integrated into the implant surface.

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